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SCENARIO-J is a thermoregulatory model developed by Kraning and Gonzalez. Previous studies suggested that the model needed an adjustment of initial core temperature (Tcr) for individual variation and a metabolic (M) correction during downhill movements. This study evaluated the updated version of the model incorporating these new features, using a dataset collected during U.S. Marine Corps training at Quantico, VA.

Individual anthropometrics, physiological, and environmental time series data were obtained from 4 males participating in the 4-day infantry field marksmanship training. This study focused on 2-h of shooting practice, then 30-min marching including uphill and downhill movements in a moderately hot environment. The predicted and observed heart rate (HR) and Tcr were compared by Root Mean Square Deviations.

Overall, the updated features of the current model significantly improved predictions, particularly for downhill marching in the heat. However, the model consistently under-predicted HR and Tcr during marksmanship training, indicating that a solar effect or non-thermal factors may have required higher M rates during these periods. Better M estimates are required for this type of situation. Improved M input should provide more accurate simulations of physiological status and better risk assessment, thereby reducing heat injuries and improving performance of deployed military personnel.

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USARIEM TECHNICAL REPORT T04-09

PREDICTING INDIVIDUAL PHYSIOLOGICAL RESPONSES DURING MARKSMANSHIP FIELD TRAINING USING AN UPDATED SCENARIO-J MODEL

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EXECUTIVE SUMMARY

SCENARIO-J is a thermoregulatory model developed by Kraning and Gonzalez at the U.S. Army Research Institute of Environmental Medicine (USARIEM) written in the Java® program language. Previous field studies suggested that the model needed an adjustment of initial core temperature (T_{cr}) for individual variation and a metabolic rate ($\dot{M}$) correction during downhill movements. This study evaluated the updated version of the model incorporating these new features, using a dataset collected during U.S. Marine Corps (USMC) marksmanship training at Quantico, VA.

Individual anthropometrics, physiological, and environmental time series data were obtained from 4 males (age: 27 ± 1 yr; height: 177 ± 7 cm; weight: 77.3 ± 8.1 kg; body fat: 15.8 ± 3.8%, $\overline{X}$ ± 1 SD) over 4 days of infantry field marksmanship training at Quantico, VA. This study focused on 2 h of shooting practice, then 30-min marching including uphill and downhill movements in a moderately hot environment (air temperature: 29.8 ± 0.5°C; dew point: 21 ± 0.5°C). The predicted and observed heart rate (HR) and T_{cr} measurements were compared by Root Mean Square Deviations (RMSD).

Overall, the updated features of the current model significantly improved predictions of physiological measures, particularly for downhill marching in the heat. Prediction errors were reduced by 60% for HR and 25% for T_{cr} during marching. However, the model consistently under-predicted both HR and T_{cr} during marksmanship training, indicating that a greater solar effect or non-thermal factors may have required higher $\dot{M}$ during these periods. Better $\dot{M}$ estimates are required for slow movements, such as marksmanship, of subjects who experience heat exposure. Improved input for $\dot{M}$ should result in more accurate simulations of physiological status and better risk assessment, thereby reducing heat injuries and improving performance of deployed military personnel.

INTRODUCTION

SCENARIO, a human thermoregulatory simulation model developed by Kraning and Gonzalez (8), was designed to predict heat strain for a range of environmental conditions, clothing, and activities. The thermal physiology of an individual is modeled as a six-node, representing core, muscle, fat, central blood, inner vascular skin, and outer avascular skin (8). The model predicts core (T_{cr}), skin temperatures, blood flows, heart rate (HR), and sweat rates as a function of (a) metabolic heat production ($\dot{M}$) associated with work activity as determined by grade, speed of movement, load, and terrain; (b) anthropometry (e.g., height, weight, % body fat); (c) thermal aspects of the physical environment (e.g., air temperature, relative humidity, radiant load, wind speed); and (d) clothing characteristics (i.e., thermal insulation, vapor permeability). The current model (v_1.0b1) includes additional input features such as dehydration status, initial or baseline T_{cr}, and acclimatization status as individual variables.

The model was validated primarily with data collected during short-term laboratory experiments (5, 6). An example would be subjects wearing battle dress uniforms (BDU) and/or heavy protective clothing ensembles while walking on treadmills (3% grade) at a constant speed (1.34 $m \cdot s^{-1}$) in a warm environment (30 $^{\circ}C$; 25% relative humidity) for 70 min. After the initial 10 minutes, SCENARIO predictions of T_{cr} agreed well with measured T_{cr} within 1 standard deviation (SD) (5). When subjects wearing shorts engaged in 50-min bouts of intermittent exercise under hot and dry environmental conditions (49 $^{\circ}C$, 20% relative humidity), the model predictions were within a reasonable range (±1 SD), but did tend to over-predict T_{cr} (5). When compared to other thermoregulatory predictions models such as the USARIEM Heat Strain Model and the John B. Pierce Laboratory Two-Node Thermoregulatory Model, SCENARIO performed well (5). However, results from previous field studies (13, 14) suggest that for more accurate predictions, the model needs an initial input of T_{cr} to compensate for individual variability and an adjustment to metabolic cost estimates ($\dot{M}$) during downhill movements. In addition, to ensure the acceptance and proper application of the model, more evaluations of model predictions of physiological responses are needed under actual field conditions when investigators have less control over the environment, subjects, and operational conditions, relative to laboratory settings. The purpose of this study is to (*a*) evaluate the updated Java version (v_1.0b1) of the SCENARIO model incorporating new features (e.g., initial T_{cr} adjustment, $\dot{M}$ adjustment for downhill movement) using data collected during military field training; (*b*) quantify patterns of agreement and disagreement between different model predictions; and (*c*) recommend improvements for a future model.

MATERIALS AND METHODS

SUBJECTS

The subjects for this analysis were part of a larger USARIEM study of U.S. Marine Corps (USMC) test volunteers participating in infantry marksmanship field training at Quantico, VA, July 2 – 5, 2001. A subset of 4 subjects was selected after reviewing data availability during the training under the moderate hot environmental conditions (13:30 – 15:55 h EDT on 4 July 2001). The test volunteers gave their informed consent to participate in the testing in accordance with US Army Regulation 70-25 regarding the use of volunteers as subjects of research.

FIELD PROCEDURE

For examining the model sensitivity of subjects' physiological responses during heat stress, afternoon marksmanship training on a hot and humid day was selected for analysis. Subjects participated in shooting exercises for approximately 2 h, then made a 30-min return march back to their housing area around 15:15 h EDT. The march route included both uphill and downhill topography. Subjects wore the USMC utility uniform during the training, and carried a pack load of 26 ± 1.0 kg only when they marched. Water was available ad libitum, and their dehydration rates were minimal (<2%) in this study.

DATA COLLECTION

Physiological Measurements

Heart Rate and Core Temperature. HR and T_{cr} of these subjects were monitored every minute. A chest-band mounted sensor (Vantage XL model, Polar Electro, Ft. Washington, NY) was used to measure HR, while T_{cr} was measured with an ingested telemetry pill (2.2 cm x 1.0 cm; Human Technologies Inc., St. Petersberg, FL) and a Body Core Temperature Monitor Receiver (Fitsense, Inc., Wellesley, MA).

Environmental Measurements. Environmental measurements, including air temperature (T_a) and dew point (T_{dp}), were recorded every 15 min by portable weather stations (Handar Model 555 Data Collection Platform, Handar Inc., Sunnyvale, CA). March velocities were clocked over a known course by a subject. The route grades were calculated using the Quantico Military Installation Map (2). These topographic data were used with a constant terrain factor of 1.2 (2, 10) to calculate metabolic energy expenditure.

Calculated Metabolic Rates ($\dot{M}$). The previous version of SCENARIO model was designed to estimate the energy expenditure using the Pandolf et al. equation (10):

$$\dot{M} = 1.5W + 2.0(W+L)(L/W)^2 + \eta(W+L)[1.5V^2 + 0.35VG]$$

where $\dot{M}$ = metabolic rate (watts); W = subject body weight (kg); L = weight of load carried (kg); V = speed of walking ($m \cdot s^{-1}$); G = grade (%); and η = terrain factor.

However, this equation works only for level and uphill grades, and may not be suitable for movements that include downhill grades. The current SCENARIO-J implemented a correction factor (CF) for negative grades, developed by Santee et al. (12), to compensate the $\dot{M}$ (watts) by subtracting the CF from the $\dot{M}$:

$$CF = \eta[(G(W+L)V)/3.5 - ((W+L)(G+6)^2/W) + (25-V^2)] \text{ when } G < 0$$

STATISTICAL ANALYSIS

The predicted and observed HR and T_{cr} were compared using Root Mean Square Deviation (RMSD) in each individual. The RMSD was used to quantify the average difference between predicted and observed measurements across time (4).

The RMSD was calculated as follows (4):

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

where d_i = difference between observed and predicted at 1-min epoch; and n = the number of compared points. In addition to assessing model improvements, the predictions of the current improved model (v_1.0b1) were compared with the predictions estimated with the old version (v_0.61) of SCENARIO_J model.

RESULTS

SUBJECTS' CHARACTERISTICS

The age, physical characteristics, and calculated resting metabolic rates (RMR) for the 4 subjects are shown in Table 1.

Table 1. Age and physical characteristics of test volunteers

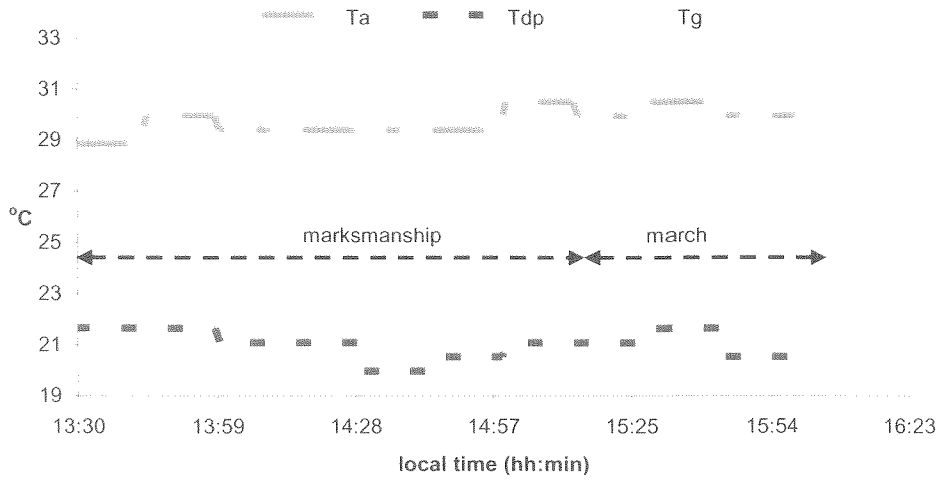
Subject	Age (yr)	Height (cm)	Nude weight (kg)	Body fat (%)	RMR (watts)
1	28	167	69.1	17.9	77
2	25	180	71.9	11.6	85
3	28	178	82.3	19.9	87
4	27	183	85.9	13.6	96
Mean	27	177	77.3	15.8	88
SD	1	7	8.1	3.8	8

RMR = Resting Metabolic Rate = watts = [(370+21.6*FFM)/1440]/0.0143, where FFM (Fat Free Mass in kg) = nude wt – [nude wt x % body fat] (1).

WEATHER

Figure 1 is the weather summary for the experimental period. Means for air temperature (T_a) and ground temperature (T_g) were 29.8 ± 0.5 ($\bar{X}$ ± SD)°C and 26.7± 0.5°C, respectively. The effect of solar radiation heating the ground during marksmanship training was delayed for approximately 2 h compared with the solar effect on T_a. Means for dew point (T_{dp}) and wind speed (not shown in Figure 1) were 21.1 ± 0.5°C and 4.2 ± 0.7 $m \cdot s^{-1}$, respectively.

Figure 1. Air temperature (T_a), ground temperature (T_g), and dew point (T_{dp}) during training period.



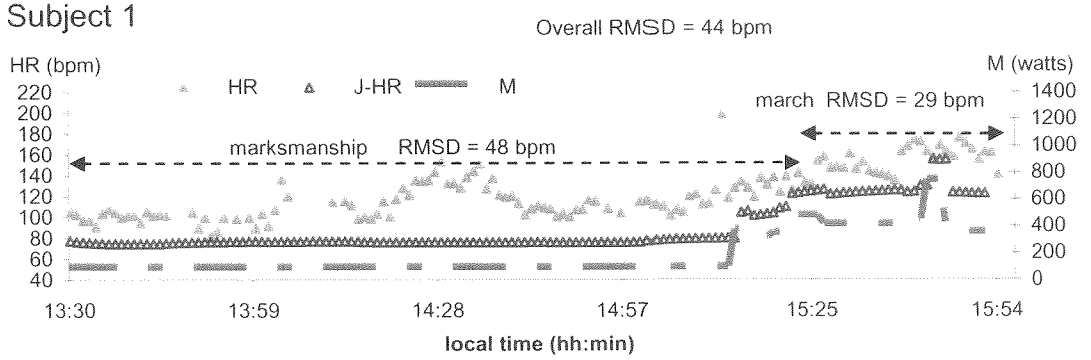
PHYSIOLOGICAL SUMMARY

Heart Rate

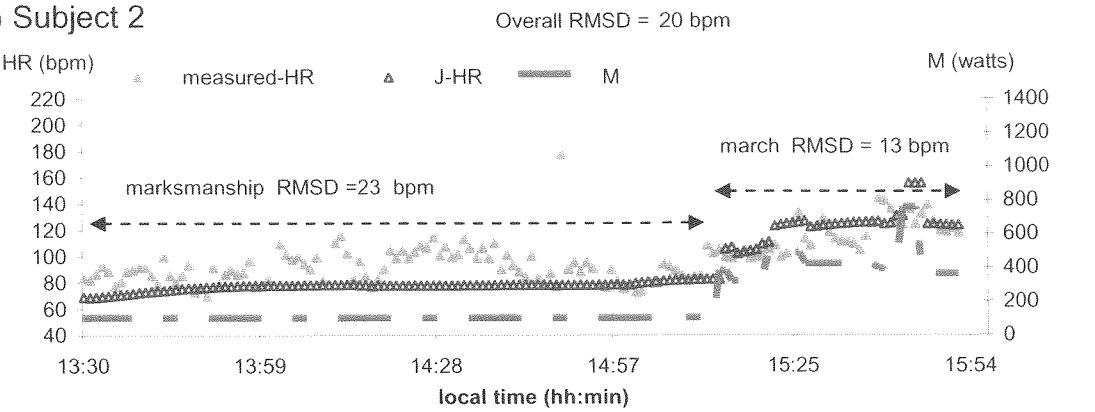
Figure 2 (a-d) shows the summary of mean metabolic rates ($\dot{M}$) and comparison between predicted and measured HR of all subjects. The average HR RMSD value of all subjects was 26 bpm during the entire period; however, Subject 1 showed more variability in HR than the rest of the subjects. The model predictions were better when subjects were marching (HR RMSD range between 13 and 29 bpm) than when they were shooting. During the period between approximately 14:00 and 15:00 hours, all of the subjects increased their HR in unison, but not in unison with model predictions, indicating a probable error in estimating activity level and/or solar load for the model. HR predictions during shooting practices were consistently lower than measured HR, and errors increased (HR RMSD = 23 - 48 bpm). In addition, despite the training break prior to the resumption of shooting exercise around 13:30, subjects' HR were higher than observed during the rest in the morning. T_a was 29.0 $^{\circ}$C at 13:30, indicating that subjects already experienced heat stress when they resumed shooting practice after the break. Another feature of HR responses observed in Subjects 1 and 2 during firing exercises were sporadic increases in HR around 15:11 and 14:40, respectively. Their HR increased approximately by 80 bpm. Subjects 3 and 4 did not show this pattern. This sporadic increase in HR may be associated with psycho-physiological stress, rather than thermo-physiological stress. Such responses also increased the apparent error rate in the thermoregulatory model predictions.

Figure 2. The summary of mean metabolic rates ($\dot{M}$) and comparisons between mean predicted and measured heart rates (HR) for all subjects (a, b, c, d)

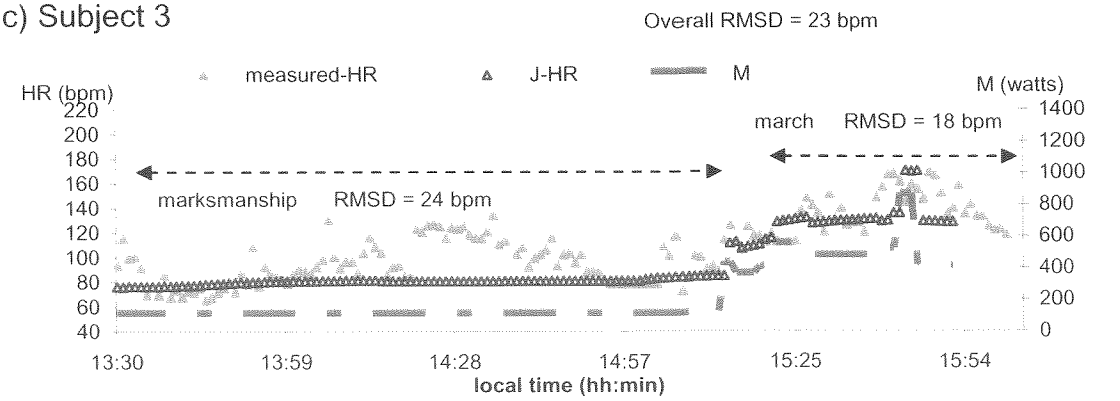
a) Subject 1



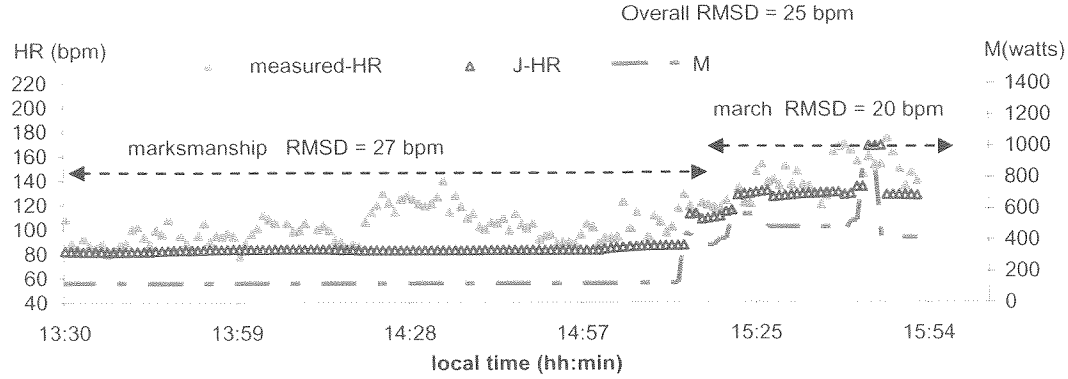
b) Subject 2



c) Subject 3



d) Subject 4

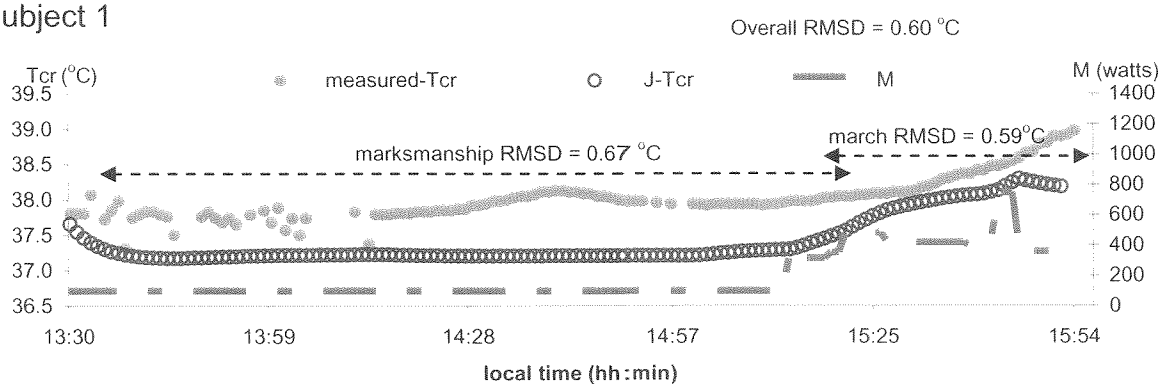


Core Temperature

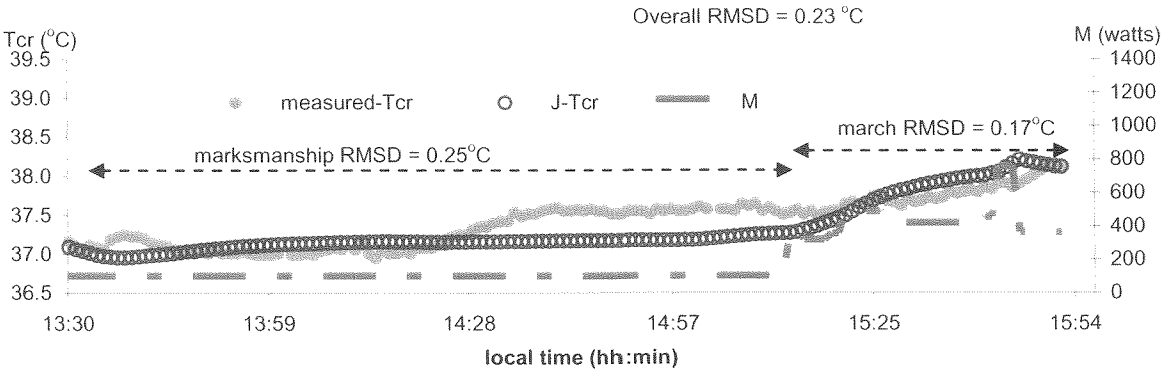
Figure 3 (a-d) shows the summary of mean metabolic rates ($\dot{M}$) and comparison between predicted and measured T_{cr} of all subjects. Average T_{cr} RMSD of all subjects was 0.57°C during the entire period. Following the same trend as the HR results, the prediction errors during marching were consistently smaller (RMSD range between 0.17°C and 0.59°C) than those during firing. The lower predictions of T_{cr} consistently observed during the marksmanship practice resulted in large prediction errors (0.25°C – 1.1°C) in all subjects. Increases in measured T_{cr} paralleled the rise of T_g between 14:28 and 15:20 (Figure 1) indicating that, despite assumed low activity, subjects did experience heat stress from ground and solar sources during shooting practice

Figure 3. The summary of mean metabolic rates ($\dot{M}$) and comparisons between mean predicted and measured core temperatures (T_{cr}) for all subjects (a, b, c, d)

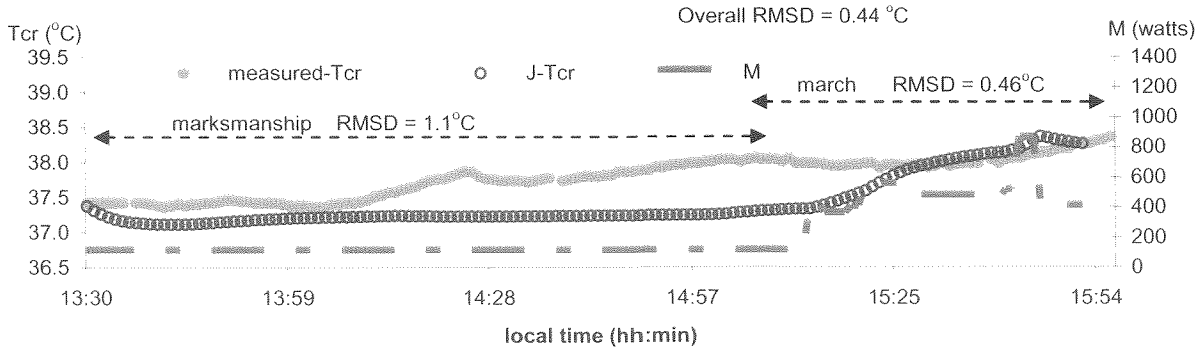
a) Subject 1



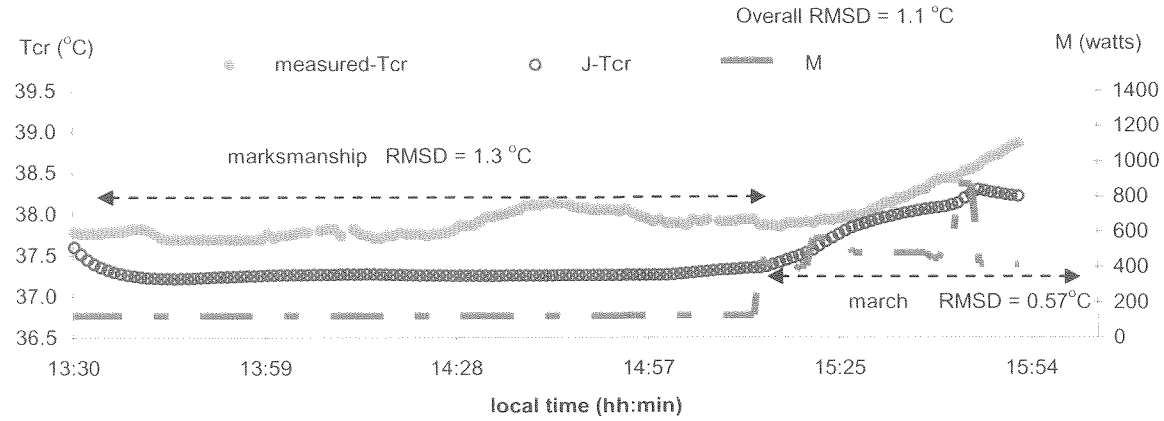
b) Subject 2



c) Subject 3



d) Subject 4



Model Improvement

Figure 4 shows the comparisons between mean measured HR and predicted HR using old (v_0.61) and improved (v_1.0b1) versions of the model. Using the old version of SCENARIO-J, prediction errors for the marching period were large during downhill movements. The updated SCENARIO-J, which incorporated a correction factor for downhill grades, significantly reduced prediction errors. However, both old and new models showed the similar error values and predicted lower physiological measures during marksmanship, thus indicating that $\dot{M}$ estimates for the model input was lower than actual energy expenditures of subjects during firing exercises.

Figure 4. The summary comparisons between mean measured and predicted heart rates (HR) using the previous (Old) and improved (Improved) models (N = 4)

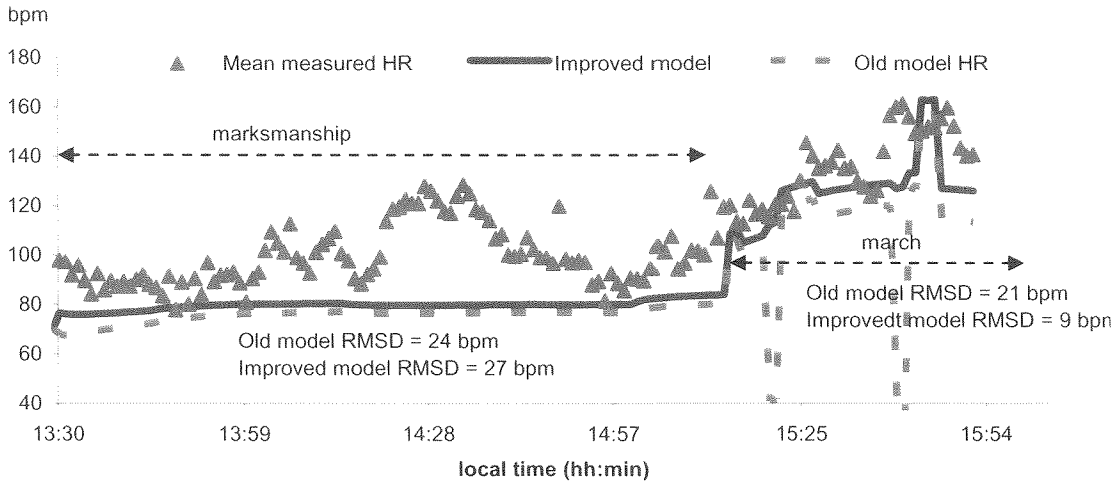
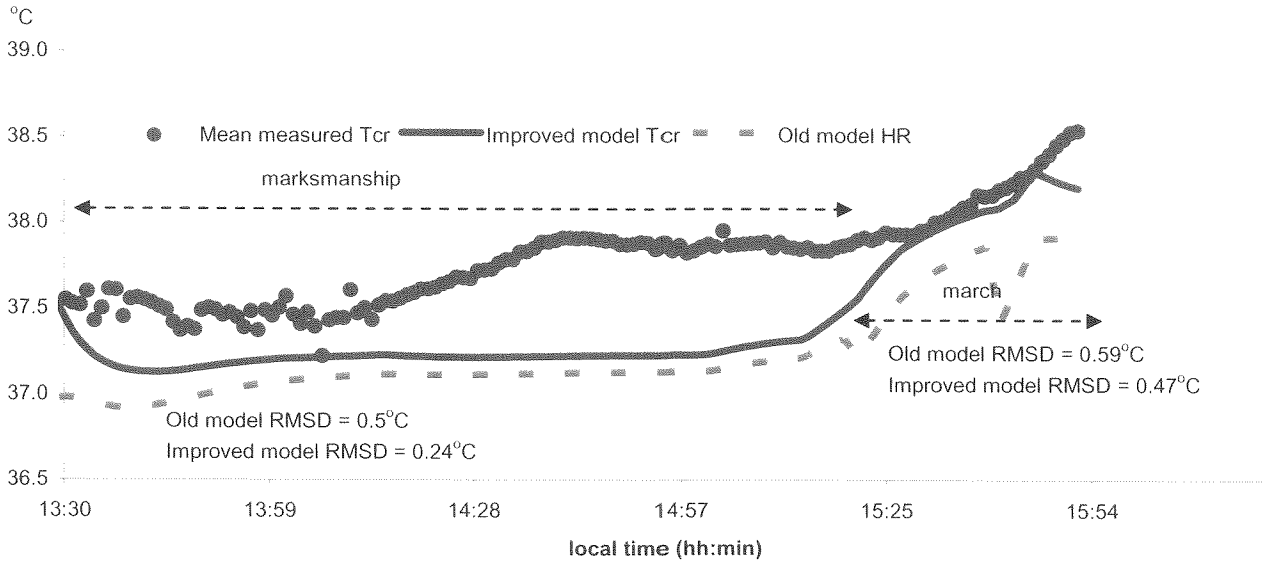


Figure 5 shows the comparisons between mean measured and predicted T_{cr} using old and improved models. The updated version also significantly improved predictions for T_{cr}; the accuracy in the current model improved by almost 50% during marksmanship training due to the adjustment of initial T_{cr}. Errors during the marching period were reduced almost by 25% by applying the correction factor for downhill movements. Paralleling the HR results, both models consistently predicted lower physiological measures during marksmanship training, indicating that subjects were exposed to heat stress during firing exercises when their movements were presumably slow and controlled.

Figure 5. The summary comparisons between mean measured and predicted core temperatures (T_{cr}) using previous (Old) and improved (Improved) models (N = 4)



DISCUSSION

The current SCENARIO-J model, with an adjustment for downhill $\dot{M}$ and the use of an initial T_{cr} to adjust for individual thermal state, significantly improved predictions of physiological measures. Based on comparisons between prior (v_0.61) and current improved versions (v_1.0b1) of the model, HR errors were reduced by almost 60% during marching periods, although errors during marksmanship did not show significant changes. T_{cr} errors were reduced during both firing and marching, by 50% and 25%, respectively.

The magnitude of model errors varied by individual; however, the patterns of errors were consistent. The model consistently predicted lower HR and T_{cr} than observed values for the firing exercises. In addition, prediction errors were greater for firing than the marching activity. The current $\dot{M}$ equations using Pandolf et al. (10) were designed under activity conditions including slow walking and standing. However, the Pandolf equation may not be suitable for the specific training situation, such as the prone and kneeling positions required for subjects to shoot during marksmanship training. During most shooting exercises, for safety purposes, movements between firing positions are short, relatively slow, and carefully controlled. At the same time, cumulative or uncompensated heat gain from solar load probably stays constant for 2 h around solar zenith. Observed physiological increases during shooting parallel the increase of T_g, despite a low $\dot{M}$, but the magnitude of the increase in T_{cr} exceeds the increase predicted on the basis of an increase in T_a. This observation suggests that subjects in their shooting positions (e.g., standing, prone, kneeling, sitting) may be absorbing heat from the ground. Thus, model prediction errors in this study indicated that a cumulative exposure to heat from air and ground warming and solar exposure resulted in increased HR and T_{cr} of subjects despite the slow movements of shooting activities.

Individual physiological variation to heat stress was also observed in this study. The rise of T_{cr} during shooting training showed that Subject 2 was largely unaffected until about 14:20, while the rest of the subjects raised their T_{cr} even in the beginning of afternoon shooting practice as a result of unrecorded heat stress or activity. Some individuals display variability within their own physiological responses as well. Sporadic HR increases were observed in 2 subjects during firing exercises. Their HR increased by 80 bpm, although the other 2 subjects did not show this pattern. Such HR variation may be associated with non-thermal factors, such as psychological stress related to their shooting performance or unaccounted work. The acute elevation of HR potentially linked to psycho-physiological stress, as well as individual HR variability, was also reported in action/defensive shooting in civilian occupations (3). To improve the accuracy of model predictions, it is important to identify the variability within and between individuals so the model can detect critical thermo-physiological stages at both population and individual levels for the prevention of heat casualties. Hydration status, heat acclimatization, an adjustment for initial T_{cr}, and a metabolic correction for downhill movement were added to the current model to better characterize individual biological

or operational conditions for the model input and predictions. However, the model is still sensitive to errors in the transition between work and rest cycles (7, 13) and low activity under the high solar load or ground warming. In addition, previous studies suggested that metabolic rates of the same activity for long hours were significantly different by anthropometry (e.g. fitness level) or gender (9, 11). An accurate assessment of $\dot{M}$ is extremely important for physiological predictions of SCENARIO-J in the improved model, as the calculation of HR and T_{cr} depends on the blood flow for aerobic metabolic heat production, work, and thermal regulation. Thus, the adjustment of $\dot{M}$ assessment for individual variation (e.g., fitness level, body fat, age) and slow activities using the current $\dot{M}$ equation, or the substitution of energy expenditure using a different equation to represent various activity levels are recommended for better physiological predictions of diverse populations.

In addition, incorporating intermittent changes into the model input, such as changes in hydration, clothing, environment, activity, or combinations of these within individuals across time, are sometimes more realistic during long hours of work, rather than assuming constant values for the inputs. For instance, deployed soldiers assigned to different activities for long hours may experience different types of thermo-physiological strains, sometimes triggered by headgear, clothing, progressive dehydration, heat (cumulative or uncompensated heat gain), heavy load carriage, or high activities like combat/assault situations. Implementing these recommendations in future models will be useful when applied to various operations and occupations including military personnel.

Finally, validating the model using physiological measures collected in the field study provided valuable information. Previous validation studies of SCENARIO using laboratory datasets indicated that the model predictions were consistent within 1 SD of observed physiological measurements (6, 8). Although they have been improved, model predictions of field data did not always provide that level of accuracy. During field experiments the investigators have less control over the environment, subjects, and operational conditions relative to laboratory settings. Consequently, there may be instrument calibration errors and other confounding factors that introduce greater variability in field datasets when compared to data from laboratory studies. In part, the greater variability of field data should provide a cautionary note to the expectations of individuals attempting to use laboratory models to predict human responses under field conditions. Given the greater level of variability observed under field conditions, expectations regarding the accuracy of modeling predictions should be adjusted to a more realistic level. Despite the limitations related to an increase in variability, the findings in this study make an important contribution by identifying additional model characteristics.

CONCLUSIONS

The current version (v_1.0b1) of the SCENARIO-J model, with the adjustment for downhill $\dot{M}$ and initial T_{cr} input for individual variability, demonstrated a significant improvement on physiological predictions. However, the model consistently under-predicted HR and T_{cr} during marksmanship training. Such prediction errors possibly occurred, because subjects were absorbing more heat from the ground and sun in their firing positions and the current $\dot{M}$ equation for a model input might not be suitable for the particular movements such as the prone, sitting, and kneeling positions that are required for marksmanship shooting. Thus, the adjustment of $\dot{M}$ assessment for slow movements under the solar exposure or the alternative energy expenditure estimate in addition to the Pandolf equation to represent various activity levels, is recommended for further improvement of the model. Despite less control over environmental conditions during military field training, the datasets collected in this type of field study provide valuable information to identify model characteristics that may not have been evident in laboratory studies.

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